UAV OPERATION TIME MINIMIZATION FOR WIRELESS-POWERED DATA COLLECTION

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Introduction

Background

- ✓ The advantages of employing unmanned aerial vehicles (UAVs) in Internet-of-Things (IoT) wireless sensor networks (WSNs) comprise:
  (a) LoS communication (b) Wireless power transfer (WPT) (c) Collect data (CD)
- ✓ Battery-powered sensors deployed in the WSN, called ground nodes (GNs), can:
  (a) Monitor environmental (b) Transmit collected data (c) Energy harvesting (EH)
- ✓ WPT to GNs from UAV for collecting data from them enables sustainable WSNs
- ✓ **Challenges** to be addressed during UAV-assisted WPT and CD from GNs:
  (a) Limitations on battery storage and operation time of the UAV and GNs.
  (b) QoS requirements at GNs that include total system throughput.

State-of-art

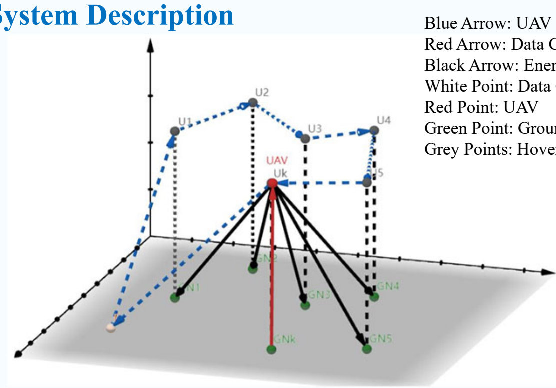
- ✓ UAV trajectory designs in UAV-assisted networks to fulfil various requirements.
- ✓ Employed UAVs to develop sustainable networks.

Innovation and Significance

- ✓ Existing works **overlooked** the possibility of WPT from UAV to GNs for CD
- ✓ **Ignored** the operation time constraint of the UAV
- ✓ Investigation of UAV-assisted **wireless-powered data collection** network.
- ✓ Operation time minimisation by optimising time allocation and UAV trajectory.

System Description

Blue Arrow: UAV trajectory
Red Arrow: Data Collection
Black Arrow: Energy Harvesting
White Point: Data Center
Red Point: UAV
Green Point: Ground Nodes
Grey Points: Hovering Locations



- ✓ Wireless-powered network that consists of one UAV and k GNs.
- ✓ UAV has 2 antennas: 1) charging GNs, 2) collecting data from GNs using TDMA.
- ✓ Locations of GNs (GNi={x_i, y_i,0}) and the data center (F={x_0, y_0,0}) are **fixed**.
- ✓ Positions of UAV above GNi is $U_i = \{x_i, y_i, H\}$, and at F is $U_0 = \{x_0, y_0, 0\}$.
- ✓ UAV takes off from data center **at constant speed v** to CD from GNs and return
- ✓ During the operation, UAV's trajectory is represented by a sequence $\boldsymbol{s}$,
- ✓ The time allocated for each GN and the data center is represented by $\boldsymbol{\tau}$
- ✓ Distance from $U_{[s]_i}$ to $U_{[s]_j}$: $d_{i,j} = \sqrt{\left(x_{[s]_i} - x_{[s]_j}\right)^2 + \left(y_{[s]_i} - y_{[s]_j}\right)^2 + \left(z_{[s]_i} - z_{[s]_j}\right)^2}$
- ✓ Flying time from $U_{[s]_i}$to $U_{[s]_j}$: $\delta_{i,j} = \frac{d_{i,j}}{v}$, and Total flying time: $T_F = \sum_{i=0}^{k} \delta_{i,i+1}$.
- ✓ UAV flies at its minimum safety altitude H except for taking off or landing down.
- ✓ Channel reciprocity and perfect CSI availability at UAV is assumed
- ✓ Channel power gain between UAV at $U_{[s]_i}$ and GN$[s]_j$ is : $h_{i,j} = \hat{P}_{LoS} d_0 d_{i,j}^{-\frac{\alpha}{2}} a_{[s]_j}$
- ✓ AWGN noise is considered with zero mean and σ^2 as the variance

Performance Metrics

- The **energy available** at GN$[\boldsymbol{s}]_i$ when the UAV reaches it is $E_i = \eta_i \sum_{j=0}^{i-1} P_H h_{i,j} \tau_i$ where η_i is GN$[\boldsymbol{s}]_i$'s RF-to-DC rectification efficiency
- With $\gamma_i = \frac{\eta_i P_H h_{i,i}}{\sigma^2}$, the throughput of GN$[\boldsymbol{s}]_i$ is: $\mathcal{T}_i(\tau_i) = \frac{1}{T} \tau_i \log_2\left(1 + \frac{\gamma_i \sum_{j=0}^{i-1} \tau_j h_{i,j}}{\tau_i}\right)$,

Problem Definition

✓ Minimise UAV operation time while satisfying throughput and time constraints

$(\mathcal{P}1)$: $\underset{s,\tau}{minimize}\ T_F + \sum_{i=0}^{k} \tau_i$, subject to

C1: $\sum_{i=1}^{k} \mathcal{T}_i(\tau_i) \geq \mathcal{T}_{th}$, $\mathcal{T}_{th}$ is the total throughput requirement.
C2: $\tau_i \geq 0, i \in \{0,1,2,\cdots,k\}$, C3: $\sum_{i=0}^{k} \tau_i - T_F \leq T$,
C4: $d_{[s]_i,[s]_j} = \delta_{i,j} v$, C5: $[s]_i \in \{0,1,\cdots,k+1\},\ i \in \{1,2,\cdots,k+2\}$.

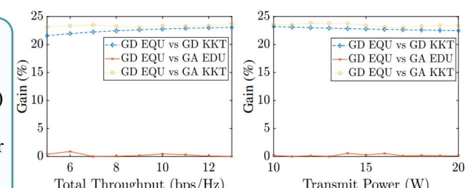
- ✓ $(\mathcal{P}2)$ is a **mixed-integer nonconvex problem**, we **decouple** it into 2 problems
- ✓ Time allocation problem $(\mathcal{P}2)$ optimizes time τ for a given trajectory:
  $(\mathcal{P}2)$: $\underset{\tau}{minimize}\ \sum_{i=0}^{k} \tau_i$, s.t. C1, C2, C3
- ✓ After obtaining the optimal time allocation, the trajectory planning for the UAV in $(\mathcal{P}1)$ can be reduced to a **travelling salesman problem** (TSP).

Proposed Joint Optimization Methodology

- ✓ Create a population of n_{pop} chromosomes to represent UAV's access order by generating sequences $\boldsymbol{s}$.
- ✓ For each chromosome, obtain time allocations $\boldsymbol{\tau}$ by solving $(\mathcal{P}2)$. This problem is proved to be convex and can be tackled by exploiting **KKT conditions**.
- ✓ Evaluate and find n_{best} high-fitness parent chromosomes with less operation time while satisfying the constraints. Generate n_{pop} new chromosomes and apply same steps until there are n_{iter} high-fitness parent chromosomes.
- ✓ Set the best high-fitness parent chromosomes across stored in n_{iter} with minimum operation time to be the **optimal UAV trajectory s^* and time allocation as τ^***.

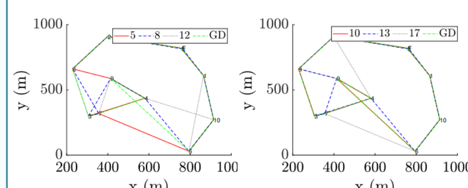
Results

- ✓ **Benchmark solutions**
  - ➢ Greedy Algorithm (GA) for trajectory planning.
  - ➢ Equal time allocation for GNs' EH and CD time.
- ✓ Better total operation time obtained for
  - ➢ Higher throughput
  - ➢ Greater UAV power
- ✓ Compared with benchmark
  - ➢ **30% improvement** in total operation time.
  - ➢ GA-based trajectory planning strategy designs provide more flexibility
  - ➢ Time allocation is more crucial.
- ✓ Low complexity GD-based trajectory design provides applicable operation time.
- ✓ Proposed GA-based trajectory design and time allocation method satisfy strict concerns about operation time.



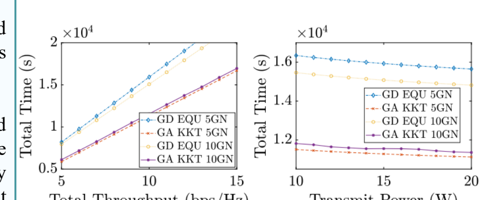
(a) Total Throughput. (b) Transmit Power.

- Variation of the minimum operation as achieved by different schemes for varying throughput requirements and transmit power.



(a) GD and GA with 3 $\mathcal{T}_{\rm th}$ values. (b) GD and GA with 3 $P_{\rm H}$ values.

- Insights on proposed trajectories minimizing operation time.



(a) Total Throughput. (b) Transmit Power.

- Improvement in UAV operation time over benchmarks

Concluding Remarks

- ✓ UAV-assisted WPT-based data collection to **minimise QoS-aware operation time**.
- ✓ **More reliable** operation of UAV, which **provides lower total operation time** while satisfying throughput requirements compared to the benchmarks

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